Space Infrastructure for 2020

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This report summarizes JASON's 1999 summer study on new approaches to the infrastructure needed for building, launching, powering and servicing earth-orbiting satellites that could be applied to military missions. We were charged to consider how recent development in broad areas of technology could be harnessed to enable new, qualitatively different ways for operating in space that would reduce mission costs---capital and operating---while increasing flexibility and performance.

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Contents

1 CONCLUSIONS AND SUMMARY

DARPA's "Orbital Express" program is a bold attempt to escape from the constraints of existing space technologies by designing a radically new infrastructure for military space operations. The goals of the program are agility, flexibility, and quick response to changing needs. We agree emphatically with these goals, but we are not persuaded that the program as presented to us during the 1999 JASON summer study can achieve them.

The main elements of the program are: (1) new building-block satellite architectures designed to enable construction, upgrades, and repairs of space systems, thereby permitting lower costs, longer operational lifetimes and new mission capabilities; (2) a system of orbiting vehicles that could service, repair and refuel operational satellites making use of the new architectures; (3) a system of energy use and storage in orbit based on regenerative fuel cells, allowing fuel to be stored and transported in the form of liquid water, used in the form of gaseous hydrogen and oxygen, and converted by the fuel cells from one form to the other as needed; (4) a new launch system based on light-gas gun technology.

The chief obstacle to achieving the goals of agility, flexibility and quick response is the high cost of launching payload to orbit. None of the above program elements is likely to overcome this obstacle. The proposed servicing vehicles and water-storage approach compound the problem because they require additional mass in orbit for system infrastructure, not active payload, although we suspect less costly alternatives exist. The light-gas gun system compares unfavorably with conventional rocket launchers, both in cost and in operational flexibility. We conclude that the goals of the Orbital Express program require other means.

We concur with DARPA that new space architectures making use of common elements, such a docking ports, communications ports and replenishable consumables

may extend mission lifetimes and capabilities by permitting upgrades and repairs.

The regenerative fuel cell technology is very promising and DARPA should support it independently of the Orbital Express program. This technology could have many useful applications in existing space missions, such as a more durable and reliable substitute for rechargeable batteries on LEO satellites.

In conjunction with an Orbital Express program, we recommend: (1) A vigorous R&D program aimed at development of cost-effective launchers—air-launched and ground-launched—using conventional chemical rockets, to reduce present-day costs of launching small payloads by a factor of ten. Such launchers would allow service, repair and refueling of operational satellites to be done from the ground at least as flexibly as from an orbiting service station. (2) A long-range study of possible "public-highway" launch systems, of which the light-gas gun is one example, to prepare for the day when the volume of traffic may be large enough to make such systems cost-effective. (3) An analytical and historical study of US space operations to determine the causes of inflexibility and slow response and to suggest practical remedies. These recommendations are described in more detail in the body of this report.

2 ORBITAL EXPRESS

2.1 Introduction

This report summarizes JASON's 1999 summer study on new approaches to the infrastructure needed for building, launching, powering and servicing earth-orbiting satellites that could be applied to military missions. We were charged by Dr. David Whelan [1] to consider how recent developments in broad areas of technology could be harnessed to enable new, qualitatively different ways for operating in space that would reduce mission costs—capital and operating—while increasing flexibility and performance. His challenge is embodied in DARPA's "Orbital Express" program, about which we received briefings from experts during our study [2] – [8].

DARPA's goals for the Orbital Express program are: (1) to increase tactical and strategic capabilities in space (earth orbits), (2) to reduce costs of orbiting systems, and (3) to enable quicker deployment of new technologies in space systems. Four areas of technology development—new space architectures, new servicing craft, new power systems, and new launch systems—make up DARPA's program. In this study, we examine and comment on plans presented to us in these technical areas. The new space architectures envisiaged in Orbital Express [1, 2] involve enhanced agility and modularity of space systems; these attributes are discussed in the remainder of this section. Section 3 describes ideas presented to us [3] on new servicing craft and our suggestion of an alternative approach. In the area of new power systems, we heard about recent developments in reversible fuel cell technology; these are described in Section 4. DARPA's principal activity in the area of new launch systems is directed toward light-gas guns. Such devices can be considered to be examples of "public-highway" launch systems, which are described in Section 5; Section 6 analyzes the cost-effectiveness of light-gas gun launch approach that was presented [7] at the sum-

mer study. The issues raised by the Orbital Express initiative go beyond military missions, prompting us to make some general observations on United States space needs which are presented in Section 7.

Launch-costs dominate the economics of space systems and will continue to do so in the foreseeable future. A 1998 JASON summer study [9] addressed this question in detail and cost analyses were presented in several briefing to this study. Figure 1 is representative of today's cost picture that emerges from essentially all analyses with which we are familiar. An important conclusion of the 1998 JASON study is that there are good scientific/engineering reasons to expect the cost/kg-in-orbit for smaller payloads—$\sim$ 100 kg—could be reduced to that of large systems, ultimately reaching something like $6000/kg-in-orbit, rather than maintaining today's large cost-penalty for low-mass launches indicated in Figure 1. On the other hand, it is hard to see how launch costs can be reduced substantially below this figure with realistic technologies now in sight. Therefore, a key watchword in all considerations of new space architectures and associated tools should be to minimize any unnecessary mass that must be lifted to orbit.

2.2 Agile Satellites

The basic goal of Orbital Express is to find new technologies that would enable increased tactical and strategic capabilities in space. One class of new missions considered is that of "agile" satellites—satellites capable of effecting orbit changes as part of their regular operational activity to be able to: (1) assemble and redeploy sparse resources onto particular areas of interest as, for example, during conflicts, (2) assemble "coherent" arrays of satellites that might permit enhanced capabilities over what could be accomplished without agility, (3) modify orbits on a random basis to deny predictability of arrival times and locations of our overhead assets. Agile satellites or on-orbit service vehicles would also permit system upgrades, refueling (more gener-

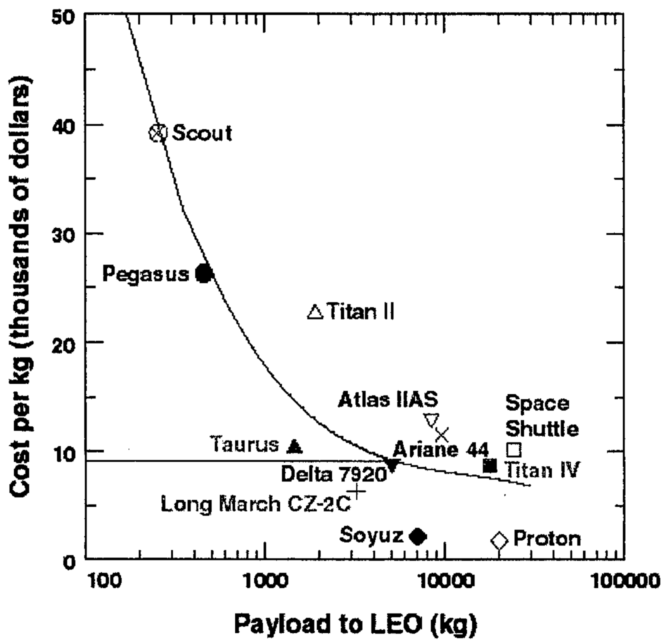

Figure 1: Current launch costs for placing 1 kg into LEO as presented by G. Stokes [2]. This material was based on AIAA International Reference Guide to Space Launch Systems, 1991 Edition. Similar cost figures are given in [9].

ally, replenishment of consumables) and repair missions for many types of satellites. Cost-savings could be realized in such systems by (1) more efficient use of valuable resources enabled by agility, (2) by life-extensions of orbiting systems through replenishment of consumables, repairs and system upgrades, (3) by economies of scale involving use of modular components with common interfaces and (4) by reducing the time between development of new technologies and their deployment in space.

Servicing satellites in orbit and changing orbits—"flying in space"—require expenditure of fuel to generate necessary thrust and, hence, substantial fuel is needed in orbit for accomplishing orbit changes. A useful figure-of-merit for describing orbital changes is Δv, the velocity change required to effect a desired orbit change. From elementary considerations[1], the fractional spacecraft mass $\Delta m/m$ expended in exhaust (fuel mass) needed to achieve a given Δv is:

$$\frac{\Delta m}{m} = \frac{\Delta v}{g I_{\rm sp}} = \frac{\Delta v}{u_{\rm exhaust}} \tag{2-1}$$

where $I_{\rm sp}$ is the specific impulse of the rocket system, $u_{\rm exhaust}$ is the exhaust velocity of the rocket and g is the acceleration due to gravity. (Note that the above equation is valid in the limit of small $\Delta v/u_{\rm exhaust}$; more generally there is an exponential relationship relating fuel mass required for a given change in velocity.)

Three types of orbit maneuvers were considered: in-plane where $\Delta v \sim$ slip distance/maneuver time, out-of-plane where Δv is some fraction of the orbital speed, and orbit "dithering" where rapid changes in orbit crossing times are needed for denial/deception purposes. In-plane maneuvers, which might include servicing or deploying a plane of satellites in some constellation, could have $\Delta v \sim few \times$m/s, while out-of-plane and dithering maneuvers would have $\Delta v \sim few \times$km/s. With typical fuel systems ($I_{\rm sp} \simeq 300$ s), these translate into fuel expenditures of $\Delta m \sim few \times 10^{-3}$ of payload mass per maneuver for servicing missions and $\Delta m \sim$ payload mass per maneuver when missions require plane changes or orbit dithering. The relative costs of these two classes of are significant: missions involving relatively slow in-plane orbit

[1]A primer on elementary orbital mechanics and rocket dynamics is given in the 1998 JASON summer study report [9]; similar analyses can be found in any introductory text on the subject.

drift can carry out many separate maneuvers with a fuel load comparable to the active payload while rapid or out-of-plane maneuvers require fuel comparable in mass to the payload for each maneuver. In the limit that launch costs dominate everything, it would make little sense to continuously supply such missions with new fuel—one would just launch fresh spacecraft for every few orbit changes because the net Δv required is comparable to that required for launch from the earth's surface!

The rendezvous and docking maneuvers that will be required for servicing an agile new space architecture were examined in two briefings [4, 5]. While intricate and demanding, the rendezvous and docking maneuvers that will be needed for flying in space with the new craft seem to be well understood.

2.3 Modular Spacecraft

In addition to agility, Orbital Express envisages highly modular spacecraft that make use of common interfaces and components which benefit from "commodity" prices and permit straightforward approaches for repairs and upgrading of components. Figure 2 indicates some of the modular components and interfaces contemplated in the Orbital Express program.

The ability to perform autonomous spacecraft repair offers possibilities for extending the useful lifetime of spacecraft. The Hubble Space Telescope is a highly visible case in point. As reported in one of the briefings [7], 62% of on-orbit failures are estimated to involve malfunctions of electronic components, many of which might be repairable by swapping relatively low-mass components.

Agile, modular space architectures should enable upgrade paths for space systems whereby new guidance, processing and communications subsystems could be installed to enhance the capabilities of a given platform and extend its operational lifetime. We were told that current satellites employ 10-15 year old technology. Integrating

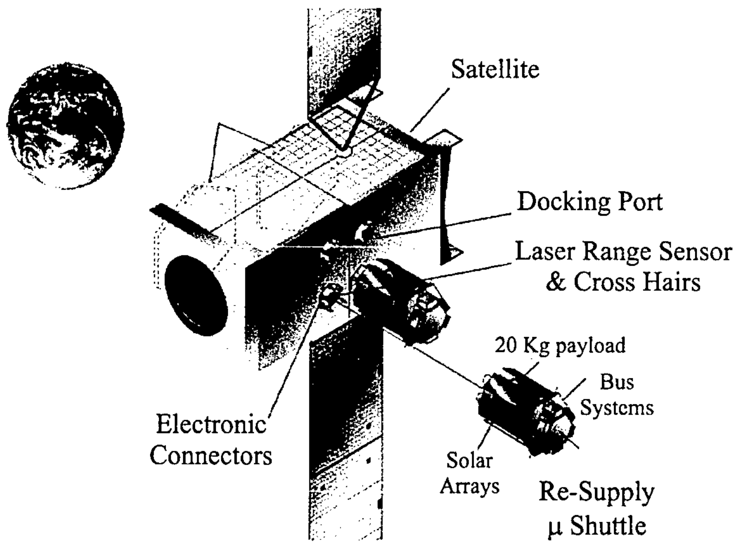

Figure 2: Orbital Express concept of modular satellite systems [1].

upgrade capability into a satellite system can reduce the age of on-board technology by allowing concurrent development of platform, processing and avionics systems. The initial launch may involve "place-holder" or "fall-back" subsystems which could later be exchanged *on-orbit* with more advanced technology as it becomes available or is needed to respond to new mission requirements. An example upgrade path would be an observing satellite of some kind that is originally configured to transmit to the ground all of its data in essentially raw form. Based on ground-based analysis of these data, an on-board processor is developed and installed onto the orbiting system, permitting substantially more processed data to be collected and down-linked than was possible when raw data alone could be transmitted.

An important component of the Orbital Express program will be the development of spacecraft interface components needed for the replenishment, repair and upgrade tasks outlined here. These components must not raise excessively the on-orbit mass overhead. Simplicity, reliability and generality of interface ports will be critical to realizing cost savings via "open systems" development of modular components and commodity prices. At a minimum, three kinds of interfaces are envisaged:

1. A mechanically stable docking port for alignment and capture, providing basic shared utilities such as power and thermal control

2. A communications port for rendezvous, docking and operations

3. A port for fuel and other consumables.

In the upgrade scenario described earlier, the new processor module might be attached to the spacecraft via the docking port, receive its data via the communications port and transmit processed results to the ground via a second communications port mounted on the processor module. One can imagine scenarios where hard docking is not required and the upgrade module station keeps in the vicinity of the original satellite.

The new spacecraft architectures anticipated in DARPA's Orbital Express program bring new systems challenges that are expected to be investigated over the course of the program. These include interactions between the main platforms, service vehicles and component modules such as thruster plumes, spin capture/control, variable inertial moments and fluid interfacing. We suggest that attention also be paid to simplifying common avionics components such as guidance and attitude sensing systems, perhaps making use of new approaches such as GPS.

3 NEW SERVICING CRAFT

DARPA has raised the issue of providing consumables replacement, repairs, and upgrades to satellites already in orbit [1]. Various missions have been suggested, such as: (1) an effective increase in lifetime divert capability for a satellite by replacing fuel for divert maneuvers; (2) upgrading electronics, especially computers, or other parts such as antennas; and (3) replacing other consumables such as cryogens. This may allow the use of smaller satellite constellations for a given degree of coverage in space and time, enable the insertion of new technology, and reduce constellation costs by shifting from launch replacement of failed satellites to repair in space.

New servicing craft and on-orbit refueling infrastructure were described by Hollander [3]. DARPA's basic approach is to launch consumables to orbiting "service stations" and, subsequently, transfer these to spacecraft using specially designed transport vehicles. This scheme is briefly described in this section where we also present an alternative approach that we believe deserves serious consideration by DARPA because it appears to offer considerably lower overhead in terms of on-orbit, non-payload mass. Our approach might be described as "just-in-time" refueling. Rather than store large quantities of consumables on an orbiting station, we suggest launching and delivering consumables to a set of satellites sharing a common orbital plane by means of single vehicle which might be reused on subsequent service missions. Our point is to minimize the orbiting infrastructure needed for servicing other craft.

3.1 ASTRO

The generic DARPA vision [1] for a servicing and refueling station in space goes under the name Autonomous Space Transporter and Robotic Orbiter (ASTRO). As the name suggests, there are two components in space: an orbiter containing supplies

to be furnished to various satellites, and a transporter to carry these supplies to the satellites.

Several contractors are studying ways to do the above missions, and one scheme under discussion [3] involves the use of a large orbiting fluid station (OFS) and a space tug. The OFS is stationed permanently in a LEO orbit and serves as a depot for consumables and other material to be delivered to orbiting satellites. The space tug delivers these materials by flying from the OFS to the satellite in need and back to the OFS. Ultimately the OFS itself must be replenished.

3.2 PBV-like Space Service Vehicle

We discuss a variant of this scheme, which does away with the space tug. It involves, either figuratively or possibly literally, the use of a post-boost vehicle (PBV) of the sort used on MIRVed ICBMs. Use of actual PBVs is limited by treaty considerations and by the fact that they are not designed for orbit, especially for prolonged orbit, but it does seem straightforward to upgrade a PBV for the service-station mission. The PBV-like space station delivers several service or fuel modules to satellites in a single orbital plane, with an accuracy in position and velocity which should allow for entry into the endgame of docking maneuvers. It could have the capability of delivering to satellites whose orbital inclinations differ by up to a few degrees, possibly as a result of previous maneuvers beginning from a single orbital plane.

Under provisions of various START treaties, MIRVed ICBMs and SLBMs are no longer allowed, and must be destroyed. Nonetheless some of the technology used for MIRVing could still be useful. Indeed, it is our understanding that PBV-like vehicles were first introduced for multiple satellite launches, and they are widely used for that purpose today.

MIRVed ICBMs, SLBMs, and even some un-MIRVed strategic missiles, use PBVs to dispense accurately a number ranging from 1 to 10 of re-entry vehicles (RVs). Each RV may weigh a couple of hundred kg, more or less. The PBV, which is in effect the final stage of the strategic missile, is released from the parent missile. It then locates itself, and with the aid of rocket motors carries the RVs from one point in space to the next, releasing them with minimum tipoff errors, so that they will reach the re-entry point with minimum error. The rocket motors could be start-stop (liquid fueled), but there is nothing in principle preventing the PBV rockets from burning continuously. The PBV contains a highly-accurate inertial navigation system (INS) capable of locating the PBV to within some tens of meters and with velocity uncertainties of less than 10 cm/sec (at least along the so-called range-sensitive axis). The need for such accuracy follows from the requirements on the contribution of RV release uncertainty on the ultimate CEP of the RV. An RV flying for 1000 seconds with a range-sensitive velocity error of 10 cm/sec will be inaccurate by 100 m. The PBV also has requirements to be able to spread its RVs over a wide region on the ground, and it is capable of a cross-range spread of perhaps 1000 or 2000 km at a range of 10,000 km. That is, the PBV has the capacity to address orbital planes differing by 5 to 10 degrees.

The existence of PBVs, therefore, tells us that it has long been possible, even without the use of GPS technology, to locate a number of sizeable objects both in space and velocity with accuracies that would allow for direct release of these objects, carrying consumables or repair modules, to LEO satellite constellations. We suggest, therefore, that the use of PBV-like service stations be considered, with modern technology. The main advantage of such a PBV-like station is that there would be no need for a space tug, only for close-range optical acquisition and docking equipment which would come into play at separations of 500 m and velocities of at most a few m/sec. (A velocity uncertainty of 5 cm/sec at service/fuel module release becomes a position uncertainty of about 250 m in one LEO orbital period.)

Actual PBVs accomplish all their RV releases in a time of half an hour, at the very most. This timeline is, of course, dictated by the suborbital nature of the mission. Moreover, the INS technology of the seventies did not involve GPS and the INS would need updates to maintain its accuracy for any longer. But with GPS and newer INS systems it would be possible for the PBV-like service station to release service/fuel modules on any desired schedule.

Evidently the PBV-like service station will not have the divert capability to address widely-different orbital angles of inclination. It is, however, useful to have some capability for sending modules to orbital planes differing by several degrees of inclination as a PBV-like station could, and not just a single orbital plane, since the satellites originally in one plane may already have made relatively small inclination changes. Indeed, such changes may be the reason that the constellation needs refueling.

4 WATER-BASED PROPULSION

A key element to making the proposed innovative, robust space architecture affordable, long-lived and flexible is the ability to replenish consumables, especially the thruster fuel supply. If the fuel in question can also power a fuel cell electric power source for the satellite, that will be even better. If, in addition, the fuel is absolutely safe when launched into space, where it can be converted into a high specific impulse chemical thruster fuel using solar power, it would seem to be too good to be true. However, it appears to us that the "Water Rocket" technologies described to JASON by Fred Mitlitsky and Andrew Weisberg[2] of Lawrence Livermore National Laboratory (LLNL) [6], fit this description.

The main technological elements of the Water Rocket are H_2/O_2 fuel cells for electric power generation, a long-lived thruster nozzle system that can effectively take advantage of the high specific impulse that can be generated by oxidizing hydrogen gas, and an electrolysis system for generating the H_2 and O_2 from water using electric power. The state-of-the-art of these technologies is a product of almost 50 years of engineering development by General Electric and Hamilton Standard (now part of United Technologies), as well as other companies more recently. The group at LLNL has been acting as a system integrator for space propulsion and other applications [10]–[14] of the technologies during the 1990's. For space propulsion, the main points can be summarized as follows. Water cannisters can be launched without concern for safety. Then the the water cannisters can be delivered to a suitably designed docking port on a satellite, enabling transfer of the water to an internal tank immediately or as it is needed. The water can be converted to the energy storage state, gaseous H_2 and O_2, by electrolysis using the solar panels for power, as needed to replenish these gases in their storage gas tanks at up to 2000 psi (14 MPa). The stored energy can

[2]The LLNL scientists made it clear that their work rests heavily on decades of unpublished research and development by applied scientists and engineers at Hamilton Standard.

then be released either in a thruster or in a fuel cell (i.e., to generate electricity for any purpose).

The electrolytic production of gaseous H_2 and O_2 from water is not new. Likewise, hydrogen/oxygen fuel cells are not new. The most important recent developments are a new, reliable, long-lived proton exchange membrane and the development of light-weight, high pressure storage tanks for the gases. In addition, it is now possible to produce high-pressure hydrogen with an electrolyzer without pressurizing the water using a proprietary electrochemical method developed by Hamilton Standard. Finally, a fully integrated system (reversible electrolyzer/fuel cell providing gaseous H_2 and O_2 to a small thruster and electrical energy to a variety of loads) has been demonstrated on the ground. These are the developments we describe in this section.

4.1 Regenerative Fuel Cell Systems

Mitlitsky and his coworkers describe a NASA-supported project in reference [10], the goal of which is to develop a low mass power source for a high altitude solar-rechargeable aircraft that has sufficient energy storage on board to enable level flight for many days or even weeks. This aircraft project epitomizes the potential applications of reversible hydrogen-oxygen fuel cells to projects in which low mass, high specific energy (kW-hr/kg) and safety are critical. The approach uses solar panels to power the aircraft and to generate hydrogen and oxygen gases from water by electrolysis during the day, and then uses the two gases to generate electricity in the same apparatus acting as a fuel cell to generate electricity to power the aircraft at night. The attractiveness of this approach is clear from Table 1, which compares both the theoretical (chemical only) and packaged specific energy of a gaseous H_2 /O_2 fuel cell with commonly used, as well as advanced, rechargeable battery systems. Evidently the H_2/O_2 fuel cell is expected to be at least a factor of two better than any packaged battery system by this measure, and it could be better by as much as

Table 1: Comparison of unitized regenerative fuel cells (URFC) with battery performance presented by F. Mitlitsky and A. Weisberg [6]. The battery performance figures are based on a 1993 survey carried out by A.D. Little, Inc. for LLNL.

Battery System	**Theoretical Specific Energy [Wh/kg]**	**Packaged Specific Energy [Wh/kg]**	**Comments**
H_2/O_2 URFC	3660	400–1000	URFC with lightweight pressure vessels
Li-SPE/MO_x	735	220	Novel packaging for unmanned system
Ag/Zn	450	200	Excess Zn required low charge rate
Li/$LiCoO_2$	735	150	Poor cycle life, high capacity fade
Li/$AlFeS_2$	515	150	– 400°C thermal management
Na/S	1180	150	– 350°C thermal management
Li/TiS_2	470	130	– 50% DOD for high cycle life (900 cycles)
Li/ion	700	100 (135)[a]	Projection revised November 1996
Ni/Zn	305	90	Excess Zn required, low specific energy
Ni/MH_x	470	70 (85)[a]	Projection revised November 1996
Ni/H_2	470	60	Low specific energy
Ni/Cd	240	60	Low specific energy
Pb/acid	170	50	Low specific energy

[a] Projections revised in November 1996 by Brian Barnett.

a factor of 5. This is possible in large part because of the development of reliable reversible proton exchange membrane (PEM) fuel cells that are capable of producing high-pressure gases without pressurizing the water [11, 12] and are also capable of operating in reverse, i.e., as an electrolytic cell, with little or no performance or efficiency reduction. This ability to use the cell hardware reversibly leads to the name, Unitized Regenerative Fuel Cell, URFC. The URFC system actually built for the aircraft application demonstrated a long life, > 2000 cycles, and produced gases at 2.1 MPa (1 atm = 0.1 MPa) from "static feed" (unpressurized) water. The same electrochemical $H_2/O_2/H_2O$ pumping system has now been demonstrated to 12 MPa.

Based upon its demonstrated proprietary technology, Hamilton Standard developed a 200 W electrolyzer design capable of electrolyzing 11.1 g of H_2O per hour (the water at 0.1 MPa yielding H_2 and O_2 at close to 14 MPa) with a design stack mass of 1.3 kg. A reversible version of that design (a URFC) is capable of generating close to 100 W of electrical power, with a stack mass of 1.6 kg, implying a mass penalty for reversibility of less than 25%. (A temporary water storage volume must be added to each cell. Using a catalyst at the oxygen electrode that permits reversibility of cell operation does not impact the system mass.)

Experience with UFRCs is relatively limited because they are a recent development. However, proton exchange membrane (PEM) fuel cells were used in the space program beginning in the early 1960s and have accumulated thousands of operating hours in space. PEM electrolyzers have been used for oxygen generation on submarines for many decades and millions of operating hours. The electrolyzers can be built in different ways. The present cell technology form used in the UFRCs, shown schematically in Figure 3, permits low pressure water feed and eliminates the need for phase separators, i.e., removal of water from the high pressure gas streams. Water is introduced into the cell behind a semipermeable water feed barrier membrane (WFB). The water migrates between the WFB and the electrolysis membrane electrode assembly (MEA) under the influence of a chemical potential gradient, $\Delta\mu_{\text{water}}$, which means that the water is supplied to the MEA only as it is being consumed. As

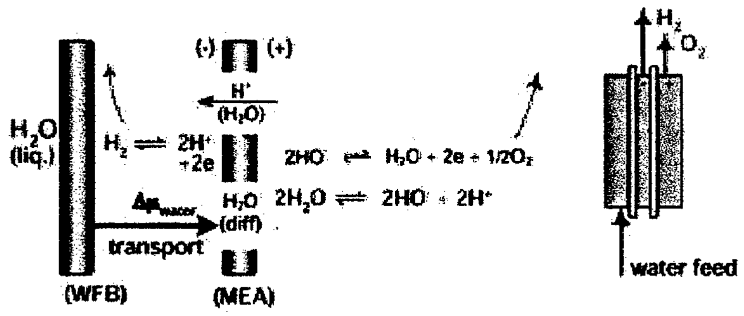

Figure 3: Static feed electrolysis: Water fed from the cathode (H_2 side) using a Water Feed Barrier (WFB) membrane. Water moves by the chemical potential gradient between the WFB and cathode surface of the membrane-electrode assembly (MEA). No phase separators are required to separate liquid water from either gas stream.

illustrated in Figure 3, the water dissociates on the anode side of the MEA, generating (hydrated) protons and hydroxyl ions. The protons migrate through the MEA and form H_2 at the cathode, while the hydroxyl ions form H_2O and O_2, with the remaining electrons being collected at the anode. The product gases come off with little water content because they are saturated at the relatively low process temperature, while the O_2 and H_2 are at high pressure. Electrochemical pumping of the gases to high pressure (by a proprietary method which was not described to us) eliminates the need for mechanical compressors, which is advantageous from both a weight and reliability standpoint. Although the electrochemical stack must be capable of withstanding the high pressure, the greatly simplified system substantially reduces the system mass relative to one with mechanical pumps and gas dryers.

4.2 High Pressure, Low Mass Tankage

Being able to produce high pressure H_2 and O_2 with low mass hardware does not guarantee that the gases can be stored without a major weight penalty. However, potential automotive application of H_2 fuel cells, as well as the high altitude aircraft and spacecraft applications of H_2/O_2 fuel cells, have pushed the development of tank-

age by Thiokol Corp. and Aero Tec Laboratories. The DOE-sponsored automotive project has as its goal achieving 34.5 MPa stored H_2 with 12% by mass of the total tank plus gas mass being H_2. Evidently progress toward the development of impermeable bladder-liners and carbon fiber composite tanks has been sufficient during the last year that the LLNL group expects the DOE goal to be achieved this year (FY2000). Work in progress involves a proprietary polymer liner within a relatively thin, laminated carbon composite tube that is directly bonded to relatively thick end domes. The tube wall thickness expected to be required for 14 MPa storage is only about 0.6 mm [14] for 5 inch diameter tubes. Of course, an automobile does not need to carry its own oxygen whereas a spacecraft does, thereby requiring two tanks. At the same pressure (34.5 MPa), the full oxygen tank will be a bit over 50% gas by mass.

4.3 Space Applications

The special advantage water-rocket technology has for spacecraft application begins with the fact that a chemical thruster which burns H_2 with O_2 to form water provides a specific impulse approaching 400 s without resorting to electrical boosting methods. The second key advantage is that the fuel can be launched in its benign form, H_2O , without requiring any extra mass associated with pressurization or safety concerns. Once in space, water can be stored in a flexible bladder contained in an insulated and heated container to maintain it in the liquid state. The bladder can provide the necessary pressure to feed virtually all of the water it contains to the electrolyzer, as has been demonstrated with H_2O_2 in a different application [13]. It was also argued by Mitlitsky et al. [6, 14] that the pressure tanks for the H_2 and O_2 can be part of the spacecraft structure, thereby reducing their effective parasitic mass. However, it is not clear that it would be a good idea to integrate the pressure tanks into the structural design of the payload portion of satellites having a variety of different purposes.

With these intrinsic advantages in mind, the viability of the water rocket technologies for the space program still requires the development of a reliable complete system that does not sacrifice the huge (factor of $2-5$) advantage of a reversible H_2/O_2 fuel cell over batteries. In addition, for space application, we must worry about whether a thruster capable of the high temperature operation needed to deliver the available I_{sp} in the presence of gaseous H_2, O_2 and H_2O can be built with an adequate lifetime. Happily, a fully integrated electrolytic propulsion system has already been ground tested [14]. An iridium coated rhenium nozzle designed and developed by NASA Lewis Research Center was tested in November, 1998 at 1.1 N of thrust using a solar-powered zero-g capable electrolyzer to supply the pressurized gases [14]. Figure 4 shows the system as tested. Although the nozzle tested was not the last word in performance, and design improvements are in the works, that successful test, carried out in a parking lot at Edwards Air Force Base, not in a laboratory environment, is very encouraging.

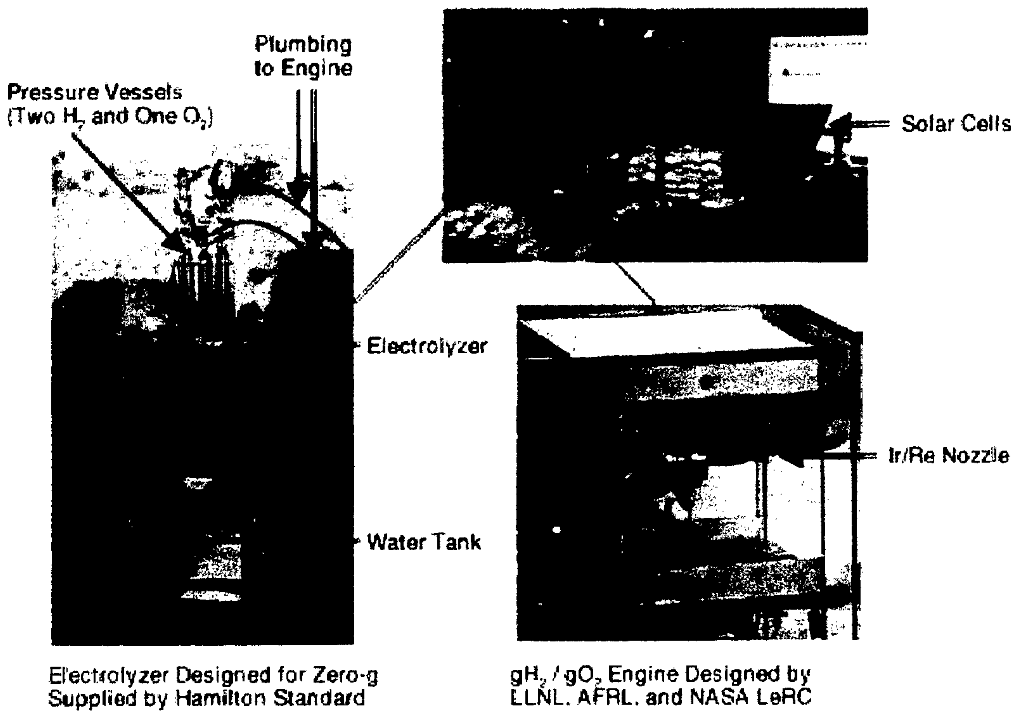

Figure 4: Brassboard test setup for Novermber, 1998 system test at NASA Lewis Research Center.

5 "PUBLIC-HIGHWAY" LAUNCH SYSTEMS

We heard briefings [7] from Harold Gilreath of Johns Hopkins University, Harry Cartland of the Lawrence Livermore National Laboratory (LLNL) and John Hunter (independent consultant formerly at Livermore) about the use of a light-gas gun (LGG) for launching space vehicles. The LGG is an example of what we call a "public-highway" launch system that attempts to minimize the per-launch cost by providing an expensive fixed-cost infrastructure. An LGG exists at Livermore and has been used extensively for experiments studying high-velocity impacts. It accelerates small projectiles reliably to velocities up to 10 km/sec. A scaled-up version could undoubtedly accelerate heavier objects to similar velocities. It is proposed that a scaled-up LGG could serve as a space-launch system, launching payloads that would be packaged in slim capsules capable of penetrating the atmosphere. The payloads would be subjected to accelerations of the order of 3000 g. This would not be damaging for bulk freight such as water or liquid propellants, or for mechanical or electronic devices with careful packaging.

The LGG has many deficiencies as a practical launch system relative to conventional rocket launch, which we discuss more thoroughly for a specific mission in Section 6; here, we summarize them briefly. Once built, an LGG can launch only a standard size and shape of payload into a standard trajectory. It has almost no flexibility to meet changing needs. It can handle only payloads that fit into narrow containers. It requires a mountain launch-site on the western shore of an ocean, with a local population that is tolerant of sonic booms. It could become substantially cheaper than conventional rocket launch-systems only if there is a large and sustained demand for launches into its allowed orbit inclination. Even with optimistic assumptions about the demand, the cost per pound launched into LEO remains of the order of a thousand dollars, comparable with the costs of rocket launch systems under similarly optimistic assumptions. For all these reasons, we do not recommend development of the gas-gun system as a part of the Space Infrastructure 2020 program.

We do endorse efforts aimed at reducing the costs of launching relatively low-mass payloads into earth orbit, be they long-range studies of other possible public-highway systems, or focused efforts to reduce the cost of air-launched multi-stage conventional rockets as described in our 1998 study [9].

The chief virtue of the LGG system is the fact that it is a public-highway system. By this, we mean the gun is like a public highway, a capital investment that has to made only once and is then available for the "public" to use. In principle, public-highway systems can become very cheap if the volume of traffic is sufficiently large. Theoretically, if the demand for launches is large enough so that the gun is firing once every five minutes, the cost per kg of payload comes down into the range of few hundred dollars, a hundred times cheaper than present-day launch costs. Nobody imagines that the demand for launches will grow to this size by 2020. But it is reasonable to make plans for a long range future in which launch traffic is large enough to make public-highway systems cost-effective. If we are considering space infrastructure for 2020 and beyond, then we should consider other public-highway systems in addition to the LGG.

The public-highway launch systems of which we are aware are gas-guns, rail-guns, ram accelerators, slingatrons, laser propulsion, and orbital tethers. This list makes no claim to be complete. Rail-guns, ram accelerators and slingatrons are similar to gas-guns, shooting payloads with high acceleration from a fixed launch-site. The rail-gun uses electromagnetic forces instead of gas-pressure to do the acceleration. The ram accelerator is a gas-gun with the gas already mixed with air or oxygen in the gunbarrel. The projectile flies along the barrel with the gas mixture igniting behind it, giving it a steady push as it accelerates. The slingatron is a spiral track that is kept rigid while each point on it moves around a small circle. The payload is accelerated around the track, keeping in step with the circular motion. At the end of the acceleration, the payload flies off the end of the track into space. The rail-gun, ram accelerator and slingatron share the main deficiencies of the gas-gun.

They are inflexible in their launch trajectories and in their requirement for payloads with standardized shape and packaging.

The remaining two public-highway launch systems are quite different, not requiring high accelerations or standardized payloads. The laser propulsion system consists of a large (gigawatt class) fixed laser on top of a mountain. It serves as a public highway for spacecraft carrying engines that can convert the energy of the laser-beam into thrust of water propellant. Each spacecraft carries only a small tank of water propellant instead of chemical fuel. A toy model of a laser-propelled spacecraft was flown successfully by Leik Myrabo in 1997–1998. The model flew up to 75 feet in air, using a ten-kilowatt laser supplied by the US Air Force at White Sands. The model weighed two ounces. If the spacecraft weight is proportional to the laser power, then a gigawatt laser should be able to launch spacecraft with a take-off weight of five tons, carrying one or two tons of propellant and one or two tons of payload. Since the acceleration is modest, human passengers might be included in the payload.

The orbiting tether system is being explored by a company called SEDS [15]. It has the virtue that it can be deployed incrementally, its capabilities increasing gradually as it grows. The idea is to have an orbiting cable with its center of gravity in LEO, one end pointing down and the other end up. A payload launched into a suborbital trajectory from the ground is caught by the bottom end of the cable, hoisted up the cable in an elevator powered by solar energy, and then released at the top end of the cable into a higher orbit. A system of such cables could transfer payloads efficiently from suborbital trajectories to GEO or beyond, without using chemical propellant. Energy could be recovered from payloads moving down the cables. In this way the cost of moving payload from earth into space could be reduced by a large factor, the initial launch into a suborbital trajectory requiring only a single-stage rocket. Like other public-highway systems, the orbital tether system becomes cost-effective only when the volume of traffic is large enough to keep it busy.

We recommend that public-highway systems for launching into earth orbit should be included as subjects for further study and research in any plans for future space infrastructure. Large expenditures and aggressive development are not needed. The purpose should be to have public-highway systems ready for serious development when the demand for launches becomes large enough to justify their cost. Until that time comes, it would be foolish to make choices between the competing systems.

6 LIGHT-GAS GUNS (LGG) vs. CONVENTIONAL ROCKET LAUNCH

In this section, we compare the potential benefits of using a light-gas gun (LGG) for multiple launching of space vehicles instead of many launches of conventional rockets. In particular, we compare these two approaches for the reference mission described in the briefing by H.E. Gilreath [7]. The reference mission services 32 orbital planes of 16 satellites each, with one spare satellite per plane. Orbital parameters are 600 km circular, 90 deg inclination.

The "payload" for the LGG is a service vehicle with a mass of 250 lb and a volume of 6 cu-ft. It exits the gun barrel at 7.0 km/s, exits the atmosphere at 6.4 km/s, coasts to 700 km, arriving at 5.4 km/s, and then a solid rocket motor boosts its velocity to 7.5 km/s, appropriate for a circular orbit. Accompanying the stated velocity profile are mass reductions as follows:

1500 lbs	exit muzzle
1320 lbs	after sabot discarded
830 lbs	after heat shield is jettisoned
280 lbs	upon orbital injection after burn of 550-lb rocket
250 lbs	payload in orbit after jettison of attitude control system.

The briefing is unclear, but it shows that of the 250 lbs delivered to orbit, the mass "available for payload" is 7.9 lb. Presumably this is the electronics and RF package for the telecommunications mission. By comparison, the Iridium spacecraft has a mass of 1226 lb, and 40% of that—490 lb—is available for payload [7]. Two reasons for the very small payload fraction in the case of the LGG-launched package are the structural mass, assumed to be 39% to handle the 2500 g acceleration, and the power, at 26%. The latter is dominated by NiCd battery mass at 60 Wh/kg, compared with NiMH at 85 Wh/kg (from Table 1) for more modest launch accelerations. If NiMH were used in a more typical 19% structure fraction, "available for payload"

could become about 81 lbs. Relaxing the shape requirement would allow further savings.

The point is that a "250 lb payload" from the LGG provides very different capability on orbit from a "250-lb payload" launched by rocket. In another section of the hard-copy of the briefing [7], we find the statement "The initial estimate for the RF payload: 280 watts required; 380 lbs." This is a spectacularly large mismatch with the mass "available for payload: 7.9 lbs". Because of the high acceleration and the requirement for a long, dense payload, an LGG approach has only one possible superiority over rocket launch, and that is the potential cost to orbit.

In a second document [16] ones finds a "Spacecraft Design Study Summary" (p. 11):

- Servicing mission
  - Payloads of small mass (10 kg) can be useful for a servicing mission.
  - Conceptually, servicing missions can be done with relatively simple, shortlived spacecraft.
  - The technology is ready; pieces are ready to come together for a (conventionally-launched) demonstration.
- Gun-launched spacecraft
  - High acceleration mostly affects the structural mass fraction for this class of spacecraft.
  - Spacecraft packaging and material selection are the most important factors for achieving an efficient high-g design.
  - At high g-levels, payload mass decreases linearly with g-load.
  - Cost of g-hardening does not appear to be a significant factor.

But this demands careful reading. The payload mass at high g-levels can decrease linearly to zero, and the actual cost of structure to survive that g can be low, but the utility of the launch then becomes zero.

In a JASON 1998 Summer Study Report [9], the authors review the options of conventional launch and opt in the near term for massive cost reduction by the use of small air-launched expendable two or three-stage chemical rockets. For a 100-lb payload and an expected payload mass fraction in the range of 1.2%, the total launch mass would be about 8000 lb, which could be launched from an F-15. Such a system might well reach $3000/lb-in-orbit, with a fuel like methane-LOX. Of course, care will be needed at every step to hold down guidance costs by the use of GPS and low-cost accelerometers, and the like.

Most important, it seems to the group, is not so much choosing the technology but obtaining the virtues of competition. The fixed-format of an LGG system, both in terms of orbit characteristics and launch vehicle configuration, would seem to make it an unlikely candidate for substantial cost/performance improvement through competition, whereas conventional rocket launch or air-assisted launch have wide possibilities of innovation and competition.

It should be emphasized that the conventional rocket is a highly efficient means of converting chemical energy into kinetic energy of a satellite payload in low earth orbit. For instance, with a payload fraction of 1.2%, a LEO satellite speed of 8 km/s, at an I_{sp} of 300 s (exhaust speed of 3 km/s), the satellite has 7.1 times the kinetic energy per gram as the exhaust gases, so that about 8.5% of the chemical energy of the propellant is actually present in the kinetic energy of the satellite. The rest goes to residual kinetic energy of the early stages, under-expansion, and the like. Even with these losses, it is difficult to imagine a more efficient system, overall, than a staged rocket for this purpose.

The compromises necessary with the LGG are many. We have already noted the apparent necessity to choose NiCd batteries at 60 Wh/kg instead of NiMH at 85 Wh/kg, simply because NiMH batteries are deemed not likely to survive the 3000 g launch acceleration. In addition, the fixed inclination from a single gun, together with

its fixed size is a serious limitation, as is the requirement to harden solar cells, deployment mechanisms, and the like against the launch acceleration.

In our view, a small fraction of the technological activism that goes with the LGG, if applied to expendable air-launched rockets, would pay off more rapidly and with greater benefit. For instance, one could imagine using a heat shield and parachute so that guidance and any valuable parts of the rocket could be recovered and reused, with reasonable likelihood. With the flexibility of an air-launch system (which might be used for larger payloads as well, as proposed by Ukraine [17]), the benefits of a modernized and lower cost space infrastructure will be available sooner than would be the case if one needed to develop and qualify an LGG for the limited missions for which it would be suitable.

7 ORBITAL EXPRESS IN THE CONTEXT OF NATIONAL SPACE INFRASTRUCTURE NEEDS

In this section, we consider the interesting implications of DARPA's Orbital Express program for non-military portions of US space infrastructure. Civilian and intelligence, as well as military, missions will span a significant range of launch vehicle lift capability, orbital configurations, design lifetimes, and spacecraft size. Each of these has implications for the architecture, cost, and feasibility of the kind of servicing and rapid-launch infrastructure being explored under the Orbital Express program.

Payload weight can be expected to range from 30 kg "microsats" to 10,000–20,000 kg "great observatories." A critical consideration in this regard will be the availability and cost of launch vehicles to span this whole range of payload weight.

Orbital configurations required for US spacecraft in the coming decades include LEO, MEO, and GEO, but also more esoteric orbits such as L2 and interplanetary missions. Spacecraft will need to fly in extensive constellations for some needs (e.g., GPS), whereas other applications will require single spacecraft (e.g., scientific missions), or small groups of spacecraft flying in formation with extensive station-keeping. The type of infrastructure needed for on-orbit servicing changes radically depending on which orbits and constellations are under consideration.

The designed on-orbit lifetime can vary from several months (e.g., Clementine, RME) to decades (e.g., Hubble Space Telescope) depending on mission cost and goals. At present the design lifetime and consumables budgets are determined together in a self-consistent fashion, and for some missions the lifetime is constrained due to lack of consumables. Availability of additional consumables on-orbit would certainly extend the design life of many future spacecraft. However for many missions, liquid consumables are not the limiting factor and design life will continue to be determined

by factors such as the cost of ground personnel for spacecraft operations and data analysis.

Spacecraft size today includes large, expensive spacecraft, for which at most a few of each model are built; intermediate and medium sized spacecraft sufficiently economical that they can be replicated in constellations; and "smaller cheaper better" spacecraft as envisioned by NASA Administrator Daniel Goldin. One of our briefers [8] presented a chart showing that the revenue stream for spacecraft-building companies is dominated by the largest "heavy" payloads. The latter are projected to produce more than 2/3 of the total revenue stream over the coming decade. So-called "small" spacecraft are projected to be responsible for less than 10% of the total revenue stream. The situation appears to be similar to that of automakers, whose largest cars produce the bulk of the profit margin. In the light of these economic realities, market forces over the coming decade may push even operational military missions in the direction of fewer, larger, and more expensive spacecraft. If this were to take place, the lack of a sufficiently numerous on-orbit constellation would then have implications for the feasibility of specific types of on-orbit servicing capabilities.

The great variety of space needs faced by the US in the coming two decades leads us to the following recommendation:

A product of the Orbital Express program should be a specific set of straw-man operational missions that would be enabled by the new DARPA technologies.

Each of these straw-man mission statements should be accompanied by a description of the rough size and weight of the spacecraft, the size of the constellation, orbital parameters, and on-orbit lifetime enabled by servicing. The mission statements should include a view of how each mission fits into the larger national context, how it relates to other components of the national space infrastructure and estimates of the "total cost of ownership" of the system.

7.1 An Analysis Component for DARPA's Program

As described to us, the Orbital Express program includes several design studies and cost-benefit analyses related to on-orbit servicing and repair. We suggest two further analysis topics that should be included in the list of deliverables for Orbital Express:

7.1.1 Satellite failure modes

If one is aiming to extend the on-orbit life of satellites by supplying servicing of various kinds, it is important to understand what have been the most costly and common failure modes for specific classes of satellites in the past.

One of our briefers reported on a study by Tosney and Quintero [18], which showed that 62% of hardware failures within spacecraft occurred in electronics components. Electronics components could be repaired, replaced, maintained, or upgraded via on-orbit servicing missions, provided that the satellite constellation had been designed in the first place to accommodate this type of servicing activity.

Other candidates for increasing on-orbit lifetime include replacing gyros[3], as has been done on the Hubble Space Telescope, and developing sufficient understanding of "infant mortality" to improve the statistics on satellite failure in the early post-launch phase.

We recommend that a retrospective study of satellite failure modes (including infant mortality) be one of the deliverables of the Orbital Express program. Once these past failure modes are understood, it will be possible to assess which of them can

[3]Instrument gyros are such a blatant source of unreliability that one ought at least to deploy off-line spares to have greater redundancy and longevity.

be addressed by the new DARPA technologies being developed in the Orbital Express program.

7.1.2 On-orbit upgrades

One of the most attractive features of on-orbit upgrades, refueling, and servicing is the potential for extending the on-orbit lifetime of expensive space assets. If one had such capabilities today, the next generation of spacecraft would certainly be designed to have a longer on-orbit lifetime taking advantage of the new technologies.

However today, DARPA must face the question of which life-extension technologies have the highest leverage to significantly increase on-orbit lifetime. To select implementations with highest promise, we recommend the following:

DARPA should do a retrospective analysis of why various DoD satellites were turned off, replaced, or allowed to die. This experience base will give insight into which contributing sub-systems are most likely to benefit from on-orbit upgrades and repairs, and will guide the Orbital Express program in its development of key technology areas.

A briefer from Draper Lab [5] described an ongoing study of nine "typical" space missions, with a view towards predicting the impact on each mission of four servicing functions and three repair/upgrade activities. The study's structure is suggested by the diagram in Figure 5. We think this is a fruitful approach to assessing the utility of specific servicing and repair options within the Orbital Express program, and look forward to learning the outcome of the study. The retrospective analysis described above will provide an important complement to the Draper Lab study.

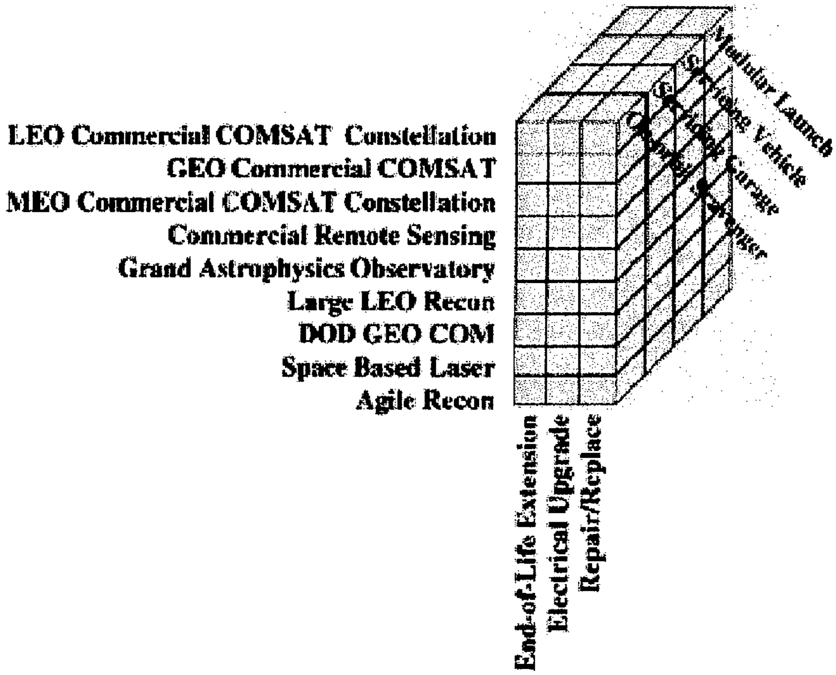

Figure 5: Schematic diagram outlining an approach being used by Draper Lab to analyze potential impacts of new infrastructure on typical space missions.

7.2 Over-arching National Concerns

Two specific areas of overarching national interest appear to us to be pressing:

7.2.1 Deterioration of the US experience base in conventional "rocket science"

The years between the end of World War II and the success of the Apollo Program brought excitement, recognition, and a wide variety of design and testing opportunities to the US community of rocket scientists. Today most of the members of this community are retiring, retired or deceased. The frontiers of science evoking public excitement now seem to be focused on other fields such as microelectronics, biotechnology and the health sciences.

In this context, we are concerned about where the rocket scientists of tomorrow will come from. Is there sufficient expertise coming out of the university system in essential fields such as rocket engine design, orbital dynamics, and spacecraft engineering?

7.2.2 Inability of the US to launch spacecraft in a timely fashion

The news media over the past six months have been full of stories of launch failures (both US and foreign). Virtually all of our scientific colleagues involved with space research have experienced launch delays, many of several years' duration. In this context DARPA's initiatives in developing alternative routes to space are appropriate. However these initiatives are quite focused, aiming at a specific sector (operational military spacecraft) and a specific type of launch capability.

It appears to us that the nation is missing the opportunity to address the broader national issues, such as the following:

- What is the long-term cost to the country of having our commercial users of space launch their payloads on rockets from China, Russia, and France?
- Does the country need to develop a new heavy-lift rocket motor? Is anybody trying to answer this question? If the country does need such a new rocket motor, should it be expendable or re-usable? (We suspect that the answer to the latter question is "expendable," but the more important point is who is analyzing the trade-offs, and how?)
- Is the reliability of US rockets deteriorating? If so, why? What should be done to improve it?

Despite the existence since 1994 of the National Space Transportation Policy Presidential Decision Directive [19], we are not aware of government actions to address

the three questions we have posed above. Responsibility is diffused among NASA, the Air Force, and the commercial sector, and there does not appear to be a policy body empowered to address these issues in a timely manner.

In the light of this leadership vacuum, DARPA's Orbital Express assumes importance as one of the only current attempts to re-think space infrastructure and its mission implications. We hope that the broader national issues can also be addressed by an appropriate mechanism with equal vigor and time-urgency.

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